Westinghouse
Lighting Institute

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UNITS OF LIGHT MEASUREMENT
PHOTOMETRY

LIGHTING INSTITUTE

WESTINGHOUSE LAMP COMPANY

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UNITS OF LIGHT MEASUREMENT

Candlepower - light power of light sources

Even after more powerful and more efficient light sources superseded candle light, illuminating power was still expressed in terms of candles. For this reason it became general practice to speak of an illuminant as producing as much light, or "candlepower", as so many candles. Obviously, the ingredients of individual candles, and the varying conditions under which they were burned, considerably affected the amount of light obtained. It was therefore necessary to provide a standard of comparison which could be used universally as a "yardstick" for measuring the lighting power of any illuminant.

This was accomplished by specifying that a light source of "one candlepower" be the light equivalent of a candle made according to definite specifications and burned under certain prescribed conditions. In this manner the term "candlepower" came into general use as the unit of measurement for the intensity of light sources. France, Great Britain and the United States have established the "International Candle" as the primary standard to be used in all light measurements and calculations.

The candlepower emitted in a given direction gives no indication of the total amount of light produced by the illuminant. Candlepower read in one direction is analogous to the depth of a pool of water at a given point - a measurement which is useful for certain purposes, but which is of no value in determining the total quantity of water in the pool. Just as it is necessary to know the dimensions of a pool and the depths at other points before its total contents can be established, so it is necessary to know the candlepower of an illuminant in all directions before its total light output can be determined.

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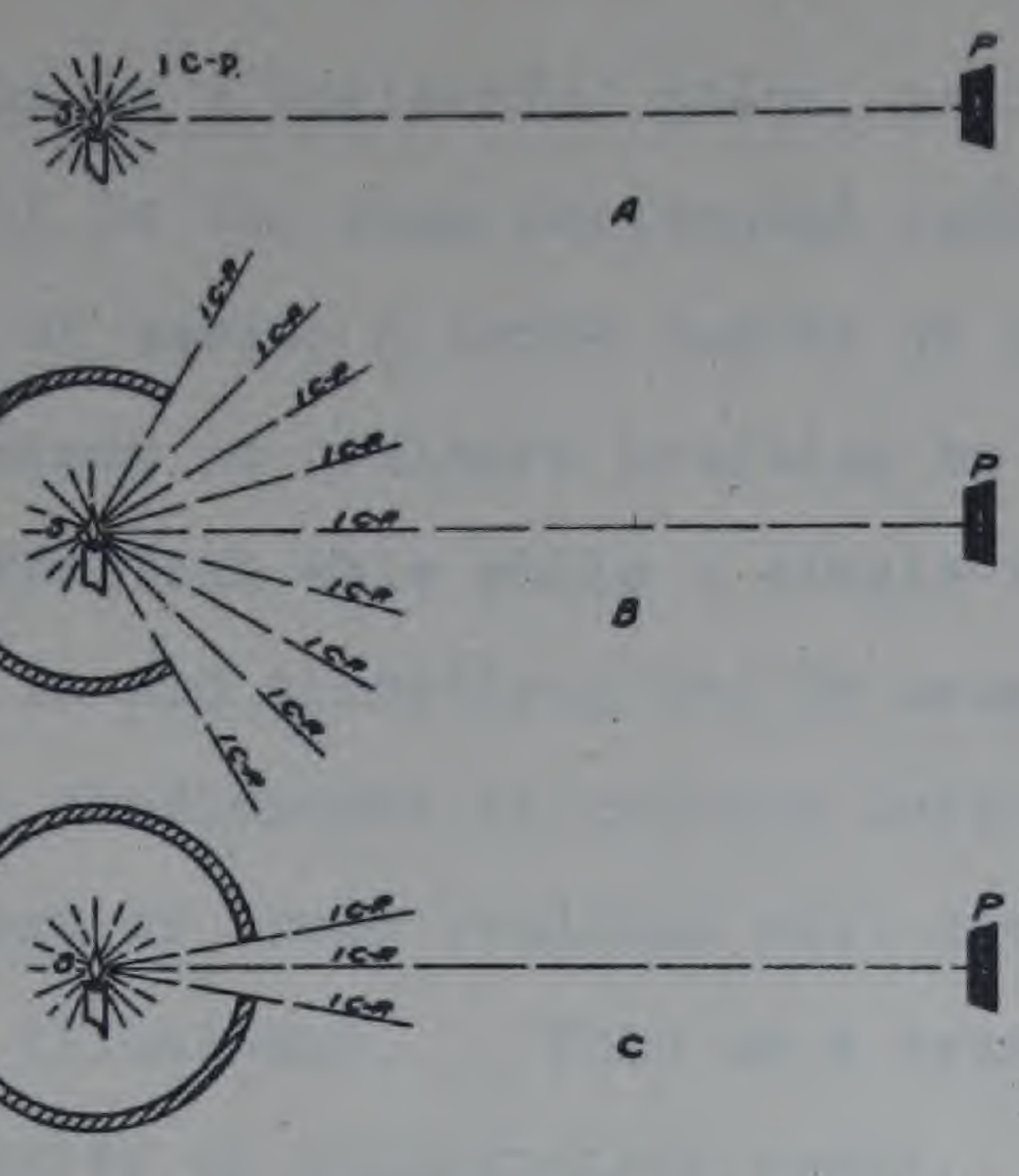


Fig. 9 - The candlepower in the direction of the photometer P is not changed by partially surrounding the light source with a non-reflecting surface.

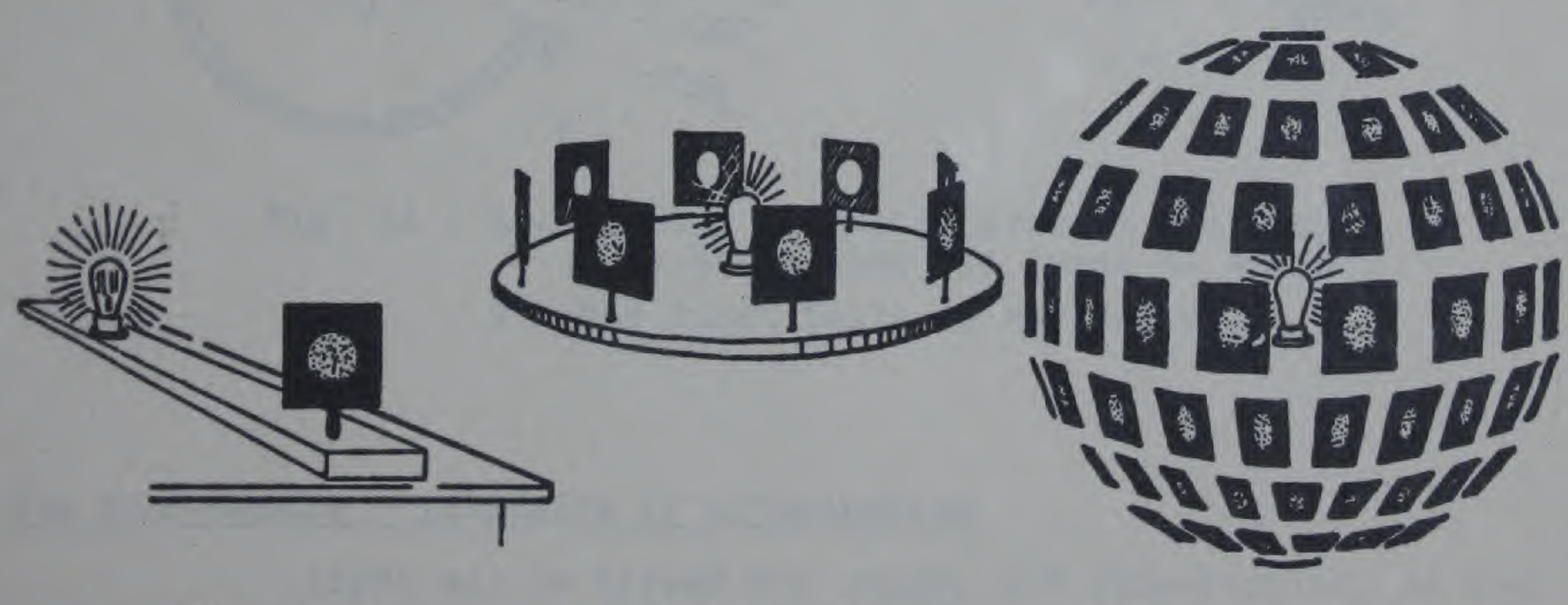
In A, Fig. 9, the photometer P* indicates an intensity of one candlepower. In B, the candle is surrounded by a sphere having a moderately large opening. Assuming that none of the light rays are reflected from the inside walls of the sphere the photometer will still indicate an intensity of one candlepower despite the fact that a large portion of the total light from the candle has been absorbed. In C, a sphere with a much smaller opening is illustrated and still more of the light is consumed by the sphere, but even in this case the light in the direction of the photometer is one candlepower. In fact, the reading will be one candlepower irrespective of the size of the opening and regardless of the quantity of light allowed to be emitted, provided the direct rays from the candle to the photometer are not obstructed.

Figure 10 indicates three ways in which candlepower measurements are ordinarily made. In A, the intensity of light radiating in one direction is measured. When a number of readings are taken

* A photometer is an instrument used to measure the candlepower of a light source, or the intensity of illumination on a surface.

at uniform intervals in a horizontal plane, as indicated in B, and then averaged, the result is the mean horizontal candlepower of the light source. Instead of taking a large number of individual readings this result is obtained in ordinary practice by rotating the illuminant rapidly about its vertical axis while a single reading is taken. The intensity of light in all directions can be ascertained as indicated in C, by measuring the candlepower at uniform intervals around the light source. An average of these readings will give the mean spherical candlepower of the illuminant. This is a true evaluation of its average light intensity or illuminating power.

In determining the light intensity of a lamp the mean spherical candlepower is usually obtained by placing it inside a sphere the inner surface of which is painted a flat white. A single reading is taken of the light that is transmitted through a small opal glass window from which the direct rays are screened. This measurement



A - Horizontal candlepower B - Mean horizontal candlepower C - Mean spherical candlepower

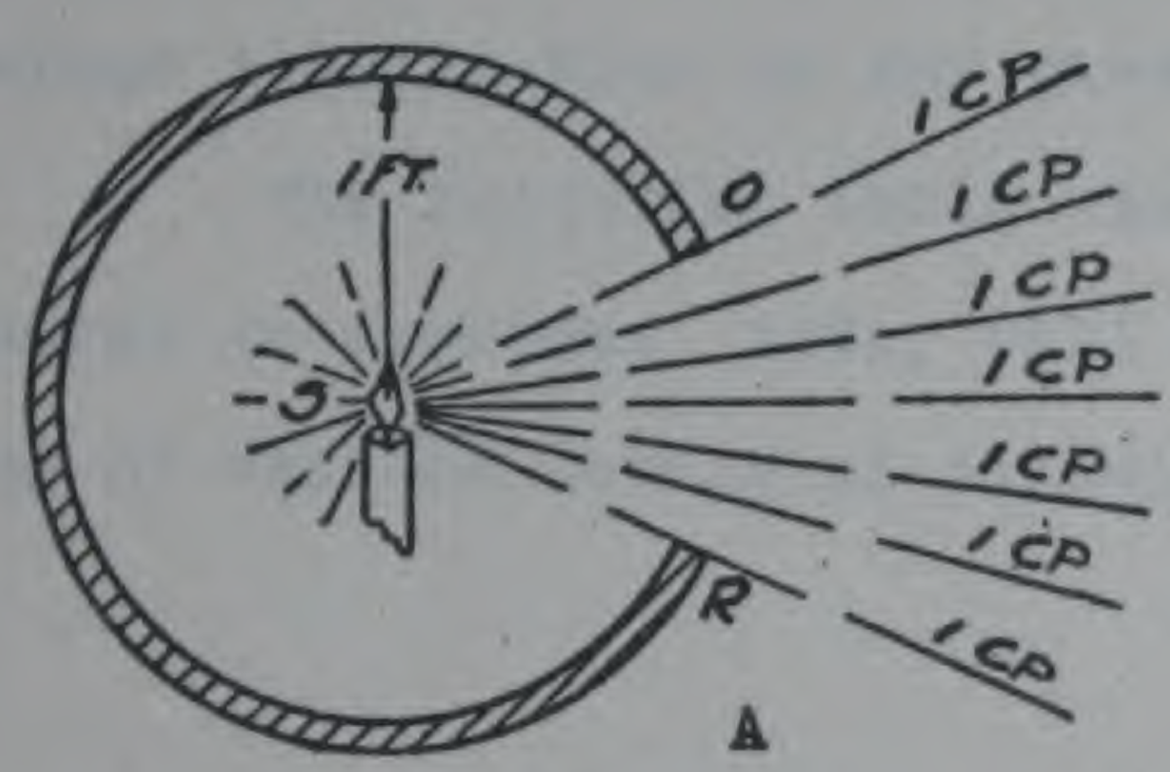
Fig. 10 - Measurement of candlepower

indicates the average candlepower in all directions because of the multiple reflections of light which occur within the chamber.

The Lumen - quantity of light

The unit used to denote quantity of light flux is the "lumen". This is the amount of light falling on a surface one square foot in area, every point of which is one foot from a source of one candlepower.

If the opening indicated in section by OR, Fig. 11, is one square foot in area, the light escaping will be one lumen; if this opening is doubled it will be two lumens. Since the total surface area of a sphere with a one foot radius is 12.57 square feet, a uniform 1 candlepower source of light emits a total of 12.57 lumens. Lumens therefore equal mean spherical candlepower times 12.57. Thus a light source of 100 mean spherical candlepower emits 1257 lumens.



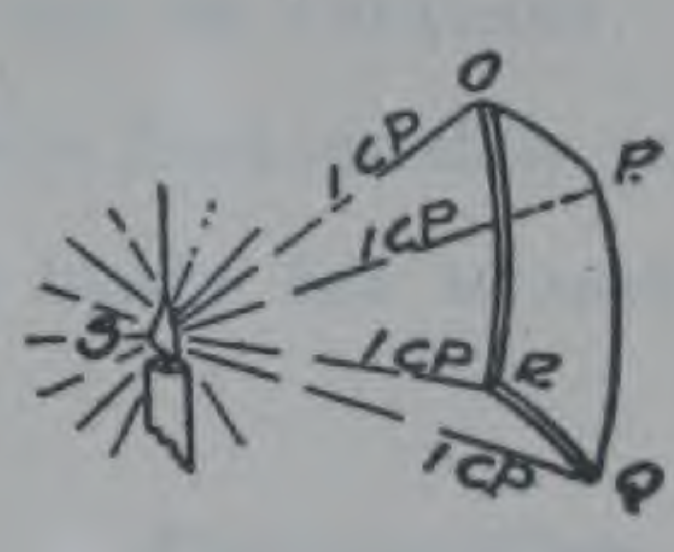


Fig. 11 - A - Opening OR has an area of one square foot and allows one lumen to escape.
B - One lumen falls on surface OPQR.

The Foot-Candle - intensity of illumination

Light may be termed the cause, and illumination, on the other hand, the effect or result. Candlepower is a measure of the cause. It therefore applies only to the light source itself and not to the effect or result obtained. The unit of measure of illumination in the United States is the "foot-candle".

A foot-candle represents the illumination at a point on a surface which is one foot distant from and perpendicular to the rays of a one candlepower light source. In Fig. 12, if the light source S has an intensity of one candlepower along the line SA, and if A is

one foot distant from the source, the illumination on the plane CD at the point A is one foot-candle.

The "foot-candle" is the unit of measurement most intimately associated with everyday use of light. A working idea of this unit can be obtained by holding a lighted candle one foot distant from a newspaper. The result will be approximately one foot-candle of illumination. A foot-candle reading applies only to the particular point where the measurement is made. By averaging the foot-candles at a number of points, the average illumination on any given surface can be obtained.

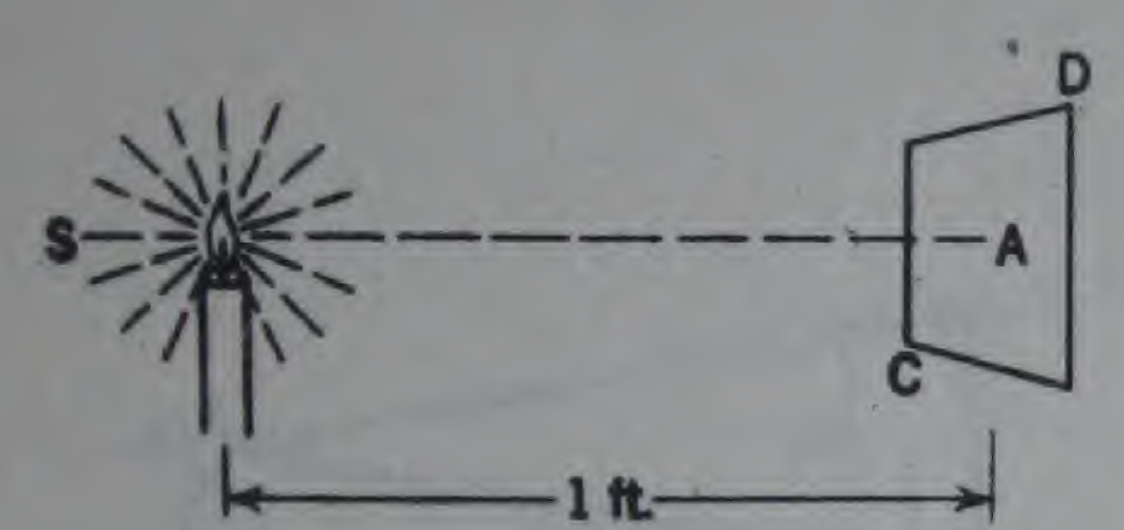


Fig. 12 - Illumination at A is 1 foot-candle.

The following table which lists the foot-candle intensities experienced in everyday life, will serve as a basis for a better understanding of various levels of illumination.

	Foot-Candles
Moonlight	.02
Street Lighting (approximately)	1.0
Lighted Store (approximately)	10 - 15
Industrial Lighting (approximately)	10 - 20
Daylight	
At North Window	50 - 200
In Shade (outdoors)	100 - 1000
Direct sunlight (June)	10,000

Care should be taken to avoid confusing the degree of illumination on, with the brightness of, a surface. A gray surface will not appear as bright as a white surface under the same illumination, since white reflects more light to the eye than gray. The brightness of an object thus is affected not only by the foot-candles of illumination on it but also by its reflection factor, i.e., the percentage of light it reflects.

The degree of illumination on a surface depends on the candlepower of the illuminant and its distance from that surface. It is

obvious that if, as illustrated in Fig. 12, instead of an intensity of one candlepower being produced along line SA, an intensity of two candlepower were produced, the illumination at A would be twice as great, and that if there were an intensity of five candlepower, the illumination would be five times as great.

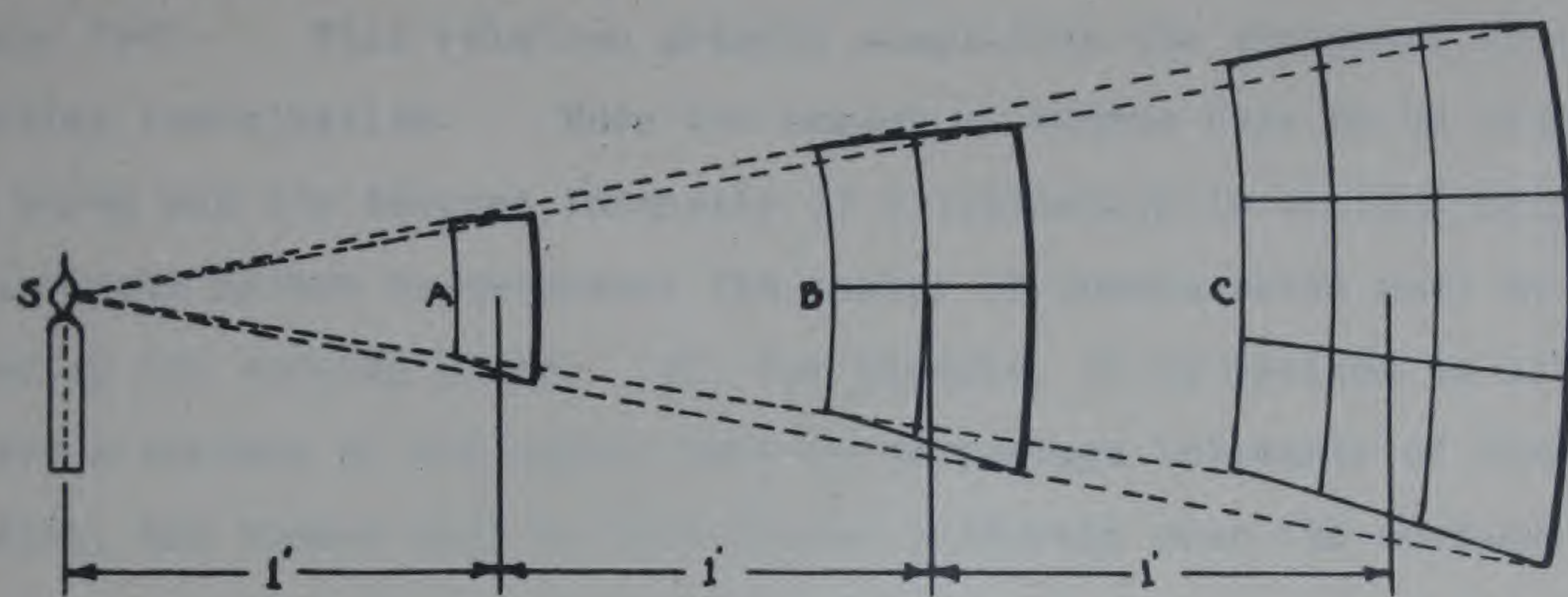


Fig. 13 - The illumination on a surface varies inversely as the square of the distance from the source to the surface.

In considering Fig. 13, if the source of light is one candlepower, the illumination on a spherical surface one foot distant, as illustrated by A, is one foot-candle. If surface A is removed, the same amount of light passes to surface B, two feet away, and here covers four times the area of A. Since light travels in straight lines and none of it is lost, the average intensity on B, two feet away is one-fourth as great as that on A, one foot away, or one fourth of a foot-candle. If B is removed and the same amount of light falls on surface C, three feet away from the source, it will be spread over an area nine times as great as A. The resulting illumination is therefore 1/9 of a foot-candle. At a distance of five feet, the illumination would be only one twenty-fifth of a foot-candle. Illumination decreases not in proportion to distance, but in proportion to the square of distance. In general, the illumination produced on a surface by a single source can be obtained by dividing the candlepower of the light source by the square of its distance from the surface. This relation is commonly known as the inverse square law

One lumen utilized so that all of its light is spread over a surface of one square foot will produce an average intensity of one foot-candle. Two lumens would produce an average intensity of two foot-candles over this same area. On the other hand, one lumen would only furnish an average illumination of 1/2 foot-candle over an area of two square feet. This relation greatly simplifies the designing of a lighting installation. When the number of square feet to be lighted are known and the desired intensity of illumination is decided upon, it is a simple matter to determine the number of lumens which must be provided on the working plane. If, for example, it is desired to illuminate a surface of 100 square feet to an average intensity of five foot-candles, 500 lumens must be distributed uniformly over the surface.

Foot-Candles x Area (Sq. Ft.) = Lumens.

Candlepower per Square Inch - brightness

Any object which emits of reflects light has brightness and is visible. In this country brightness in any given direction is measured in terms of "candlepower per square inch". Thus the brightness of a surface in a given direction equals its candlepower in that direction divided by its projected area in square inches.

The following table lists the brightness of typical light sources in candlepower per square inch and should facilitate a better understanding of this unit of measure for brightness.

	Candlepower per Sq. In.		Candlepower per Sq. In.
Gas Flame	2.5	Mazda C Lamp Filament	6,500
Enclosing Globe	2.5 - 4.0	Crater of Carbon Arc	100,000
White Bowl Lamp	13	High Intensity Arc	400,000
Frosted Lamp	50 - 60	The Sun	1,300,000

Lighting authorities are in general accord that lighting glassware suspended in the ordinary line of vision should not have a surface brightness in excess of 3.5 candles per square inch.

PHOTOMETRY

Photometry is that branch of physics which deals with the measurement of light. The more common methods and instruments employed for this purpose are described in the following paragraphs.

If a hole were cut in the curtain of a theatre and this were covered with translucent material, such as waxed paper, a person sitting in the orchestra could readily tell when the stage lights were on if the house itself were dark. The small spot would stand out in bright contrast to the surrounding surface of the curtain. If the illumination in the house were gradually increased, the spot would appear less and less luminous. At a certain point it would have the same brightness as its surroundings, appearing neither less nor more luminous than the adjacent area. On the other hand, if the stage were dark and the house were light, the hole in the curtain would appear as a dark spot. At the point where the spot seems invisible it indicates that the illumination on both sides of the curtain is of the same intensity. The ability of the human eye to recognize equality of brightness is the basis of most photometric measuring devices.

The Simple Bar Photometer

In laboratory practice, the simple bar photometer, illustrated in Fig. 14, utilizes the principles described above. A vertical paper screen, indicated by C, corresponds to the curtain. In the center of this is a grease spot which makes a small portion of the screen translucent. B is a standard source of light providing one candlepower in a horizontal direction. The horizontal candlepower of lamp A is to

be determined. By moving the photometric screen, C, back and forth between the two light sources, a point is found where the grease spot appears neither lighter nor darker than the surrounding paper on the screen. In order that the observer may see both sides of the screen

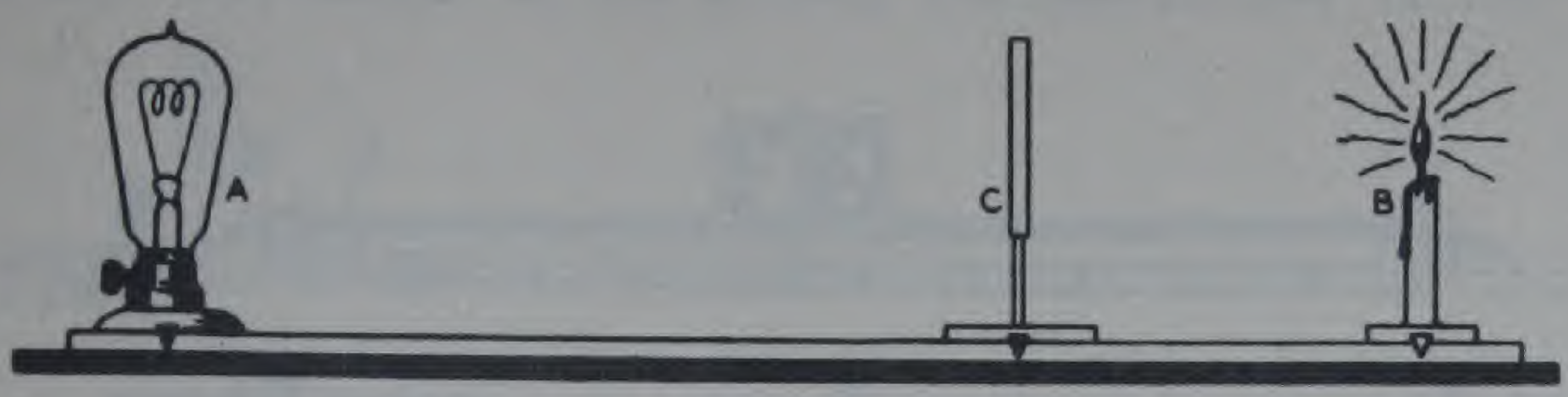


Fig. 14 - Simple bar photometer

simultaneously, oblique mirrors are placed, as shown in Fig. 15. This arrangement facilities accuracy and rapidity in testing, especially when the two light sources emit light of slightly different colors. When the screen is in a position where the spot disappears, or the two spots as reflected in the mirrors appear equally bright, the photometer is said to be balanced. In this position the illumination in foot-candles on both sides of the screen is equal. The ratio of candlepower of the two light sources then equals the ratio of the squares of the distances from each side of the screen.

$$\frac{\text{Candlepower of A}}{\text{Candlepower of B}} = \frac{(\text{Distance from screen to A})^2}{(\text{Distance from screen to B})^2}$$

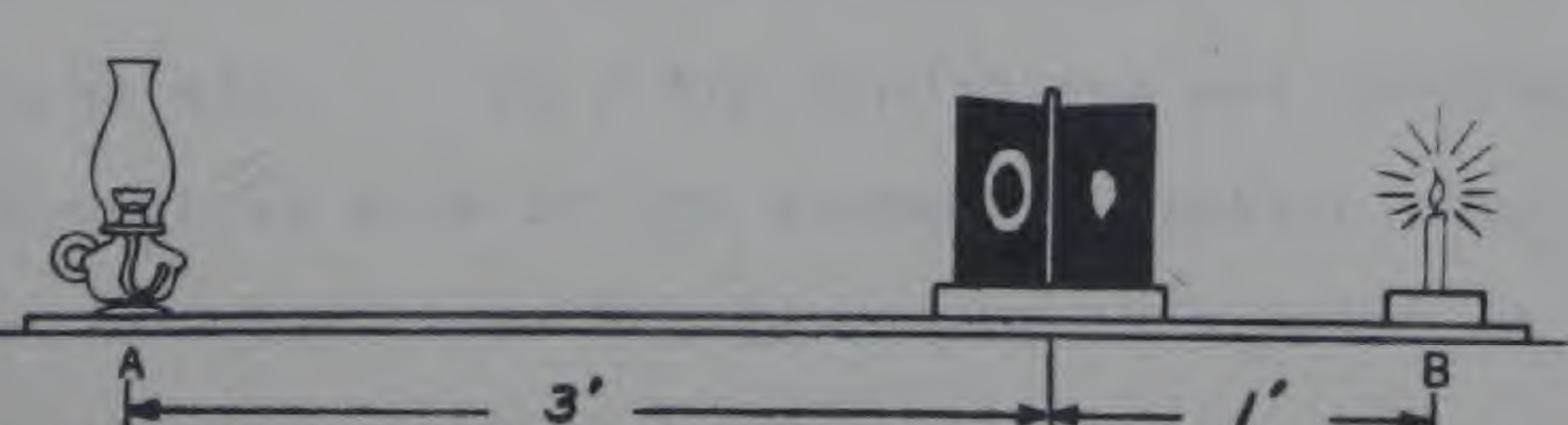


Fig. 15 - Bar photometer showing use of oblique mirrors

Assuming that the point of balance lies one foot from B (Fig. 15) and the candlepower of B is one, one foot-candle of illumination is produced on the side of the screen which faces it. Since the

photometer is balanced the illumination on the opposite side, obtained from lamp A, must also be one foot-candle. Foot-candles decrease as shown in Fig. 13, in proportion to the square of the distance for the source of illumination. Therefore if lamp A is three feet away and gives one foot-candle on the screen, its candlepower is $(3)^2$ or 9.

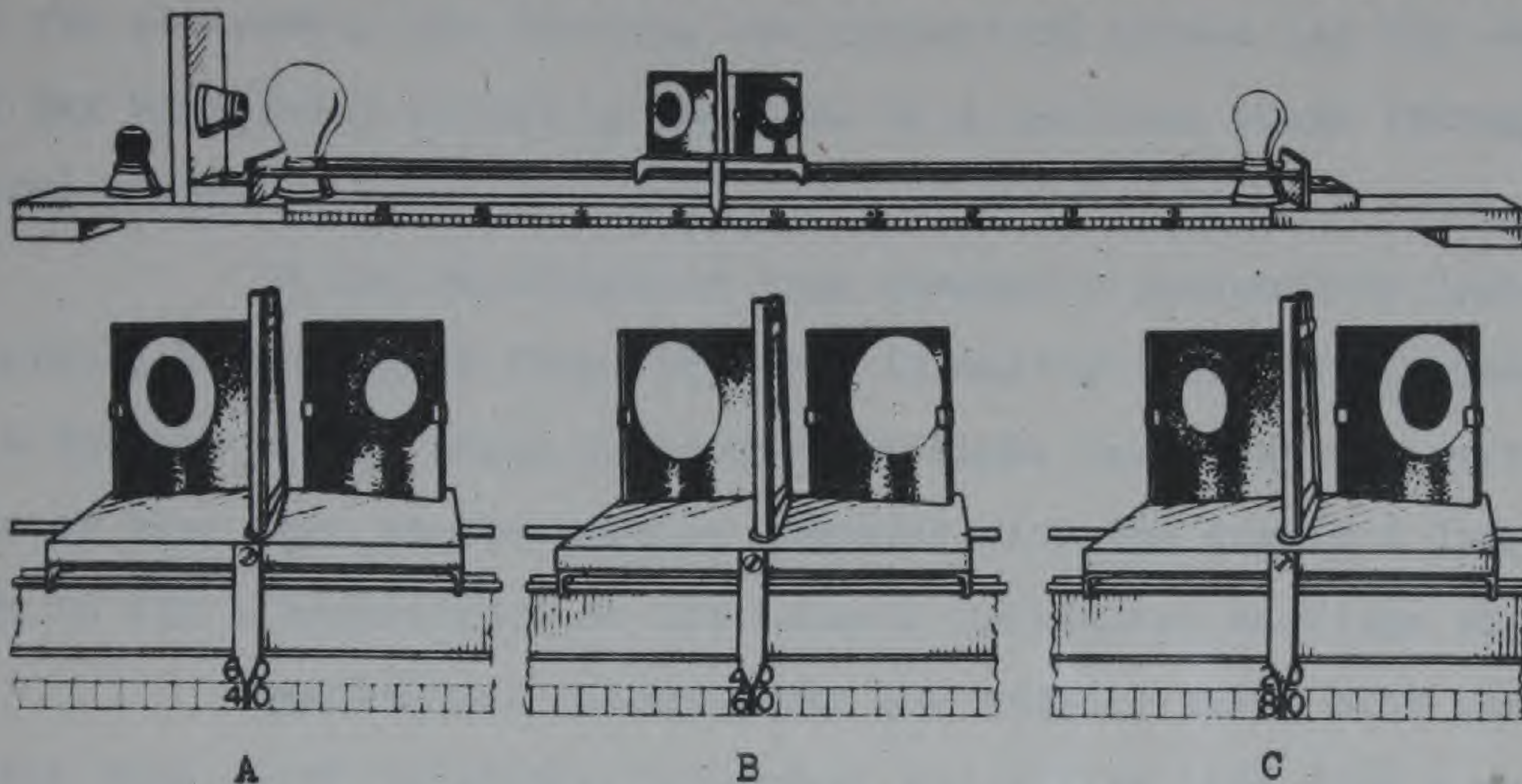


Fig. 16 - Photometer and screens.

A - Screen at left of balance point.
B - Screen at balance point.
C - Screen at right of balance point.

Fig. 16 illustrates the appearance of the photometric screen at various positions. In A the spot as viewed in the left-hand mirror is darker than its surroundings and as viewed in the right-hand mirror is lighter than its surroundings. This indicates that more light falls upon and is transmitted through the left-hand side of the screen than on or through the right side. In C the conditions are reversed; the illumination on the right side of the screen is greater than that on the left. Somewhere between these two positions is a point at which the spot ceases to be visible as shown in B.

The apparatus used in making photometric readings as described in the preceding paragraph is known as a Bunsen photometer. For more accurate photometric measurements the grease spot screen is replaced by a somewhat more complex piece of optical apparatus.

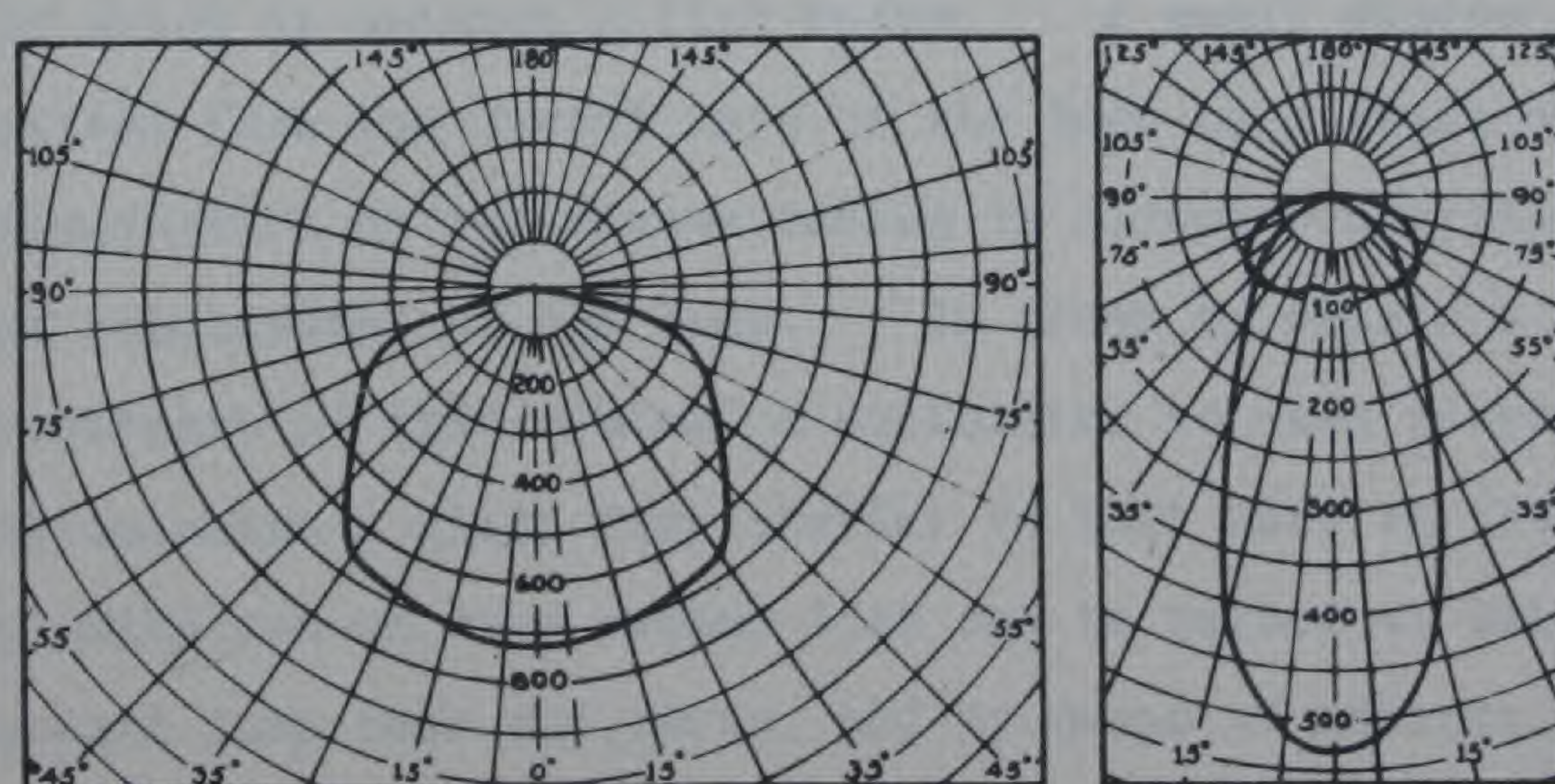
The Distribution Photometer

Some photometers measure simply the average horizontal candlepower of an illuminant. To determine the candlepower at angles above or below the horizontal, the lighting unit is held in a vertical position and the rest of the photometric apparatus hinged in such a way that the photometer bar carrying the comparison screen and the standard lamp may be readily tilted up and down in a vertical plane through any desired angle.

In the Westinghouse Lamp Company's photometric laboratory the distribution photometer (Fig. 18) used in making tests of lighting units has a movable mirror which redirects the light rays from any particular angle so that they may be readily compared with the standard lamp (not shown in the illustration) on the movable horizontal carriage at the right.

Candlepower measurements are usually taken with photometers of this type at 5° intervals throughout the entire 180° from a point beneath the test unit to a point directly above it. A properly weighted average of these readings gives what is termed the mean spherical candlepower of the lighting unit.

ANGLE	CANDLE POWER
0	732
5	725
15	705
25	690
35	665
45	560
55	460
65	380
75	103
85	19
90	0



A B C

Fig. 17 - Methods of recording candlepower measurements.

The tabulation in Fig. 17-A shows the results of a test on a 200 watt Mazda C lamp equipped with an RLM Standard Dome reflector. In this table 0° refers to the reading taken directly beneath the unit.

The candlepower in this direction was found to be 732. Likewise 90° represents a measurement taken on the horizontal; due to the type of reflector chosen the candlepower at this and higher angles was zero. In Fig. 17-B a curve is shown. It will be noted that at each angle the curve passes through a point which corresponds to the tabulation in Fig. 17-A. The curve cuts the 0° line at 732, passes through 35° at 665 and cuts the 65° line at 380, etc. This graph is commonly known as a candlepower distribution curve.

The area of a distribution curve is not a criterion of the total light output of a source. In Fig. 17-C both curves shown are taken from units giving exactly the same total lumens of light. A distribution curve serves merely to show the candlepower at various angles.

The Sphere Photometer

As previously mentioned, mean spherical candlepower and lumen output may be obtained by a direct reading in a sphere photometer, usually known as an Ulbricht Sphere, illustrated in Fig. 18. In this photometer the lamp to be measured is placed at the center of the large sphere the inside wall of which is painted a flat white. A small window of opal glass is shielded from the direct rays of the lamp by a small opaque screen. The illumination on the window varies in direct proportion to the mean spherical candlepower of the lamp. In order to obtain a measure of the brightness of this window, a photometer is used in which a standard lamp illuminates a glass disk similar to that used in the window. The illumination on this second disk can be varied at will by moving the standard lamp back and forth, and by means of mirrors in the photometer the two disks may be viewed simultaneously and balanced. Thus the total lumens or mean spherical candlepower of a lamp can be determined at one reading.

Larger spheres similar in principle to the Ulbricht Sphere are used to measure the light output of various types of lighting equipment. The Westinghouse Icosahedron (the twenty sided enclosure

shown in Fig. 18) will measure with two readings the output or efficiency of complete lighting units, even the large fixtures used for street lighting.

Lumens Per Watt - light source efficiency

It is necessary to measure not only the candlepower of a light source but also its **efficiency.** In modern electric lamps this is expressed in lumens per watt, which is simply the number of lumens of light flux produced divided by the watts of electrical energy consumed. For most lamps these values are based on measurements made in the sphere photometer.

The efficiencies of ordinary Mazda lamps in common use vary widely. The 10 watt S-11 bulb lamp produces 7.7 lumens per watt as compared to 30 lumens per watt for the 10 K.W. G-80 bulb lamp. The average efficiency of the lamps used in the United States is somewhat over 10 lumens per watt.

PORTABLE LIGHT INTENSITY METERS

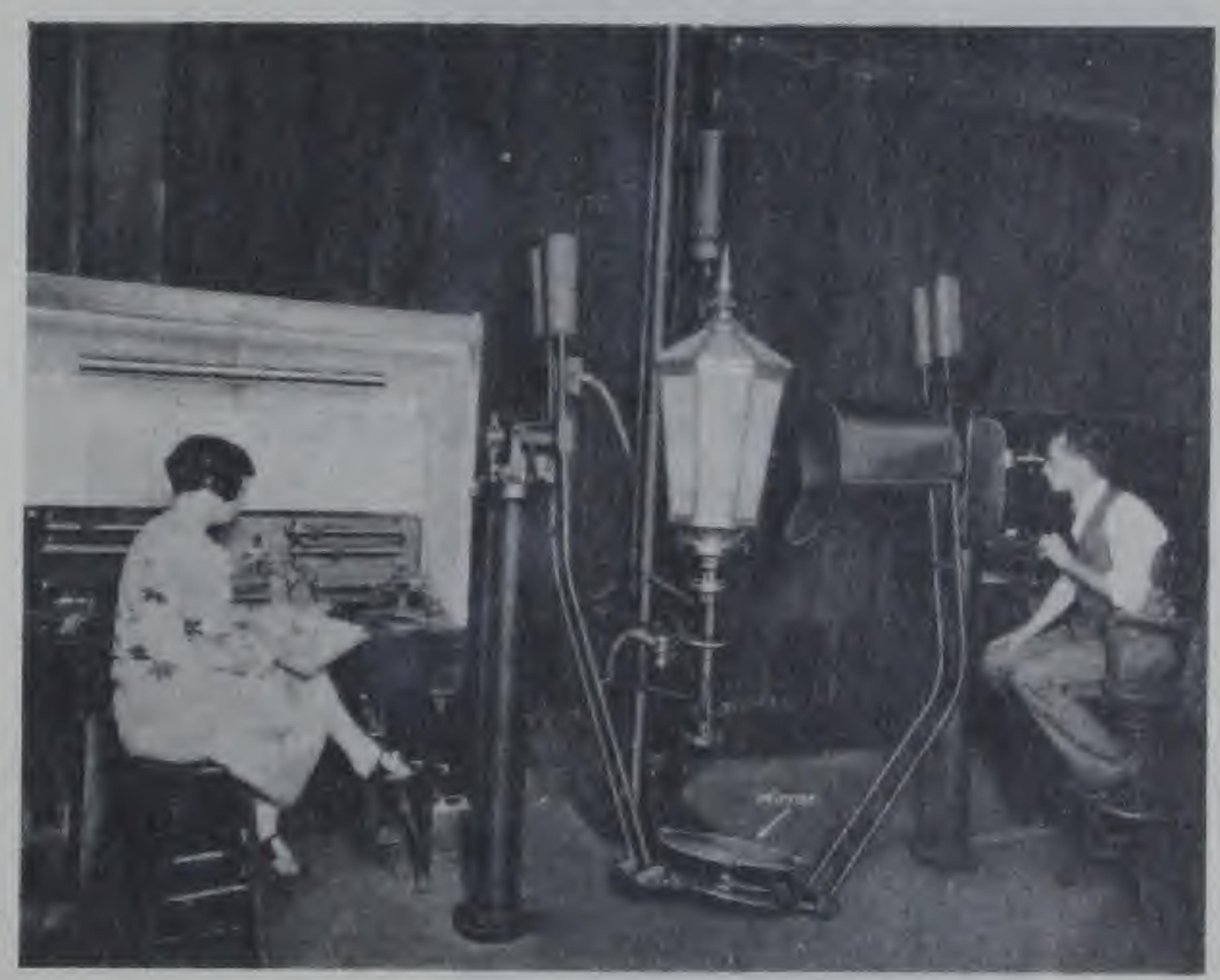
Ability to see depends upon the levels of illumination on objects at which we are looking. In our daily use of light, therefore, we are more interested in measurements of illumination on the working planes than in candlespowers of sources of light. There are a number of instruments available (Fig. 19) with which to measure foot-candles of illumination on surfaces.

The Foot-Candle Meter

This instrument is a small, conveniently portable photometer, sufficiently accurate for ordinary illumination measurements. A miniature incandescent lamp, operated from a dry-cell battery, is at one end of a trough which is covered by a screen having a series of translucent spots similar to the grease spot of the simple bar photometer. When the lamp in the meter is turned on, the spots on the screen are illuminated. Their brightness depends upon the distance of each from the

Icosahedron
(Equivalent to a
10 foot sphere photometer)
Westinghouse Lamp Company

Distribution Photometer
Westinghouse Lamp Company



Ulbricht Sphere Photometer

Fig. 18 - Photometers for measuring light output (distribution or efficiency) of incandescent lamps or other lighting units.

Using Foot-Candle Meter

Foot-Candle Meter

Photo-electric Cell Photometer

Sharp-Millar Photometer

Macbeth Illuminometer

Fig. 19 - Photometers for measuring the intensity of illumination.

QUESTIONS

1. In your own words, what is your conception of the term candlepower? Foot-candles? Lumen?

2. Upon what fundamental law is the principle of the photometer based?

3. Give, briefly, some of the commercial applications of the photometer.

4. What is the principle of the foot-candle meter?

5. How does the accuracy of reading and ease of manipulation of the foot-candle meter compare with that of a laboratory instrument?

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